

# Dark matter searches at the LHC

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*on behalf of the CMS and ATLAS collaborations*

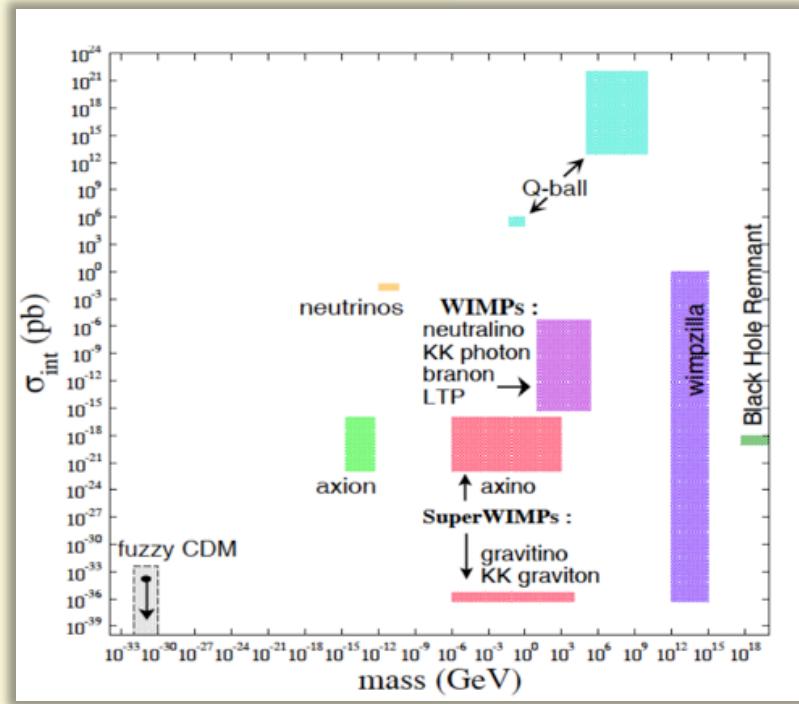
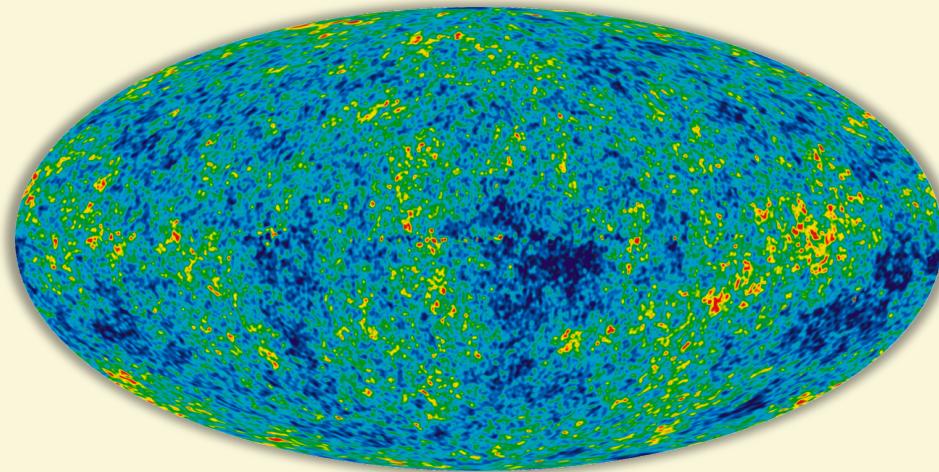


Caltech

13<sup>th</sup> International Conference on Topics in Astroparticle and Underground Physics, Asilomar, California USA

September 12, 2013

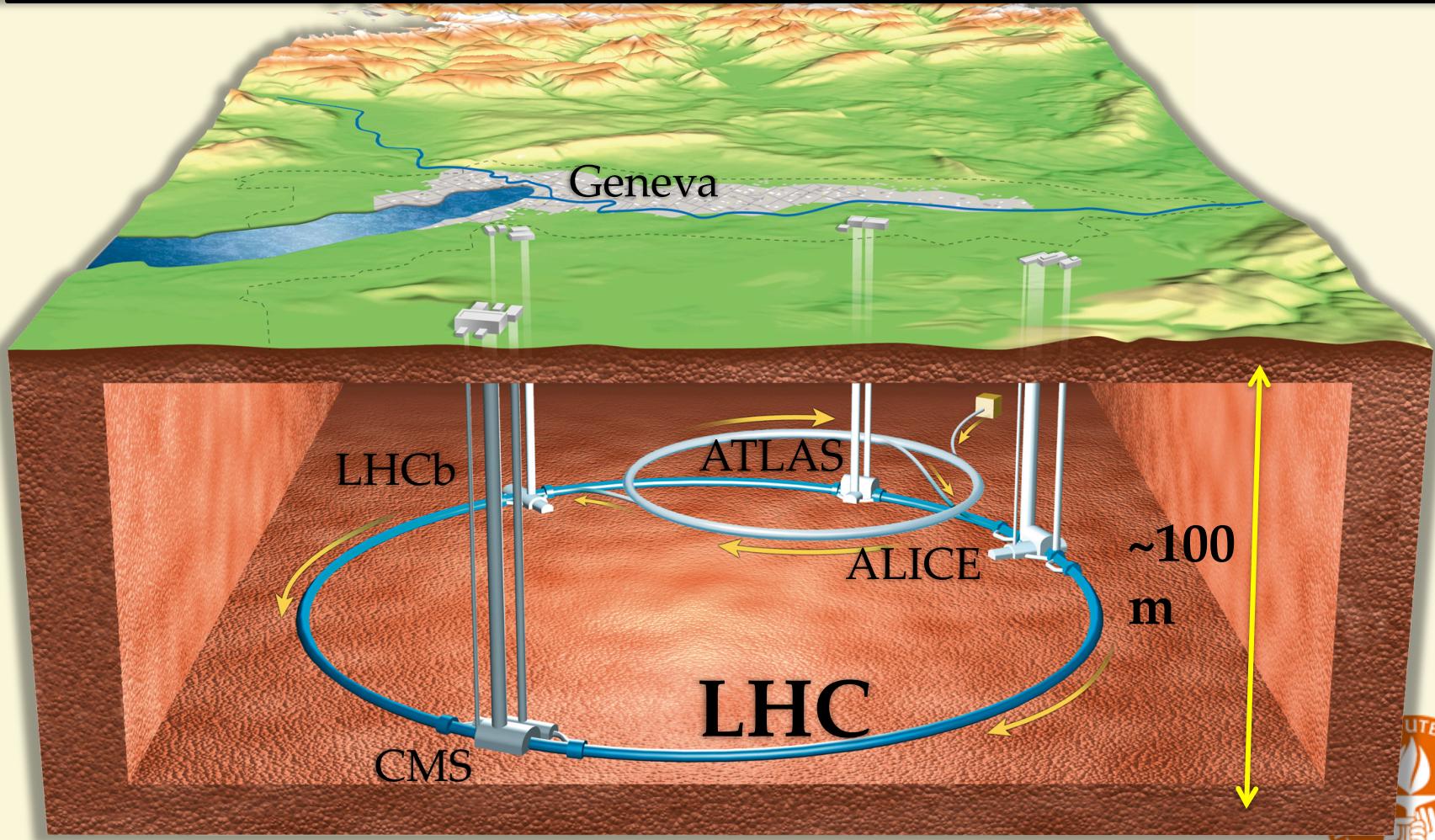
# DM Candidates



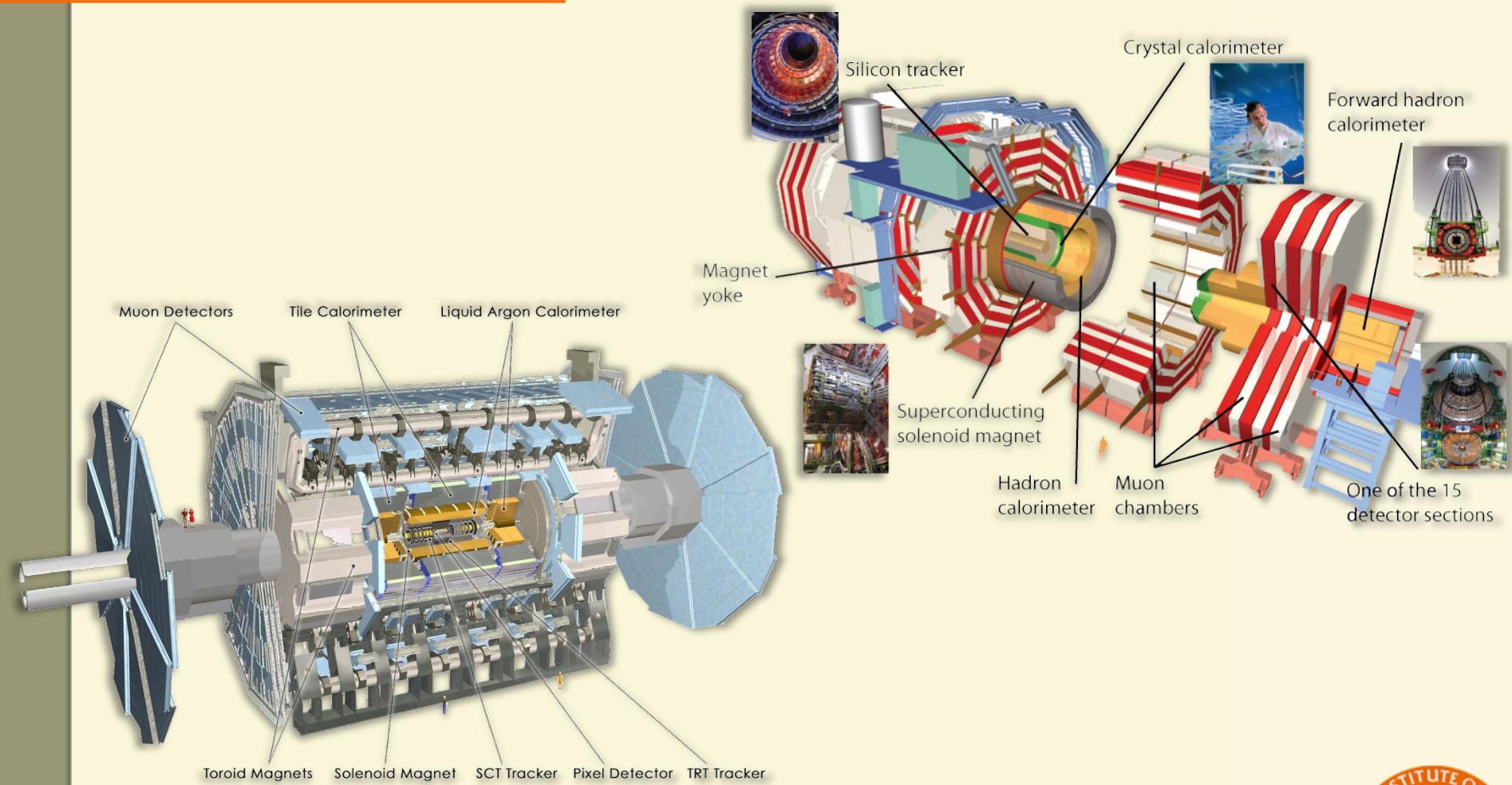
- *Many models of DM (J.Feng arXiv:10030904):*
  - WIMP: naturally arise in SUSY, UED; “WIMP” miracle  $\rightarrow$  0.1-1 TeV
  - Axion (Axino): solve strong-CP problem, can be very light
  - Gravitino: SUSY; can inherit WIMP miracle if NLSP
  - More “exotic”: primordial black holes, wimpzilla, sterile neutrino, etc

# The Large Hadron Collider

Proton-proton collisions at  $\sqrt{s}=7, 8 \text{ TeV}$  (13-14 TeV in 2015)

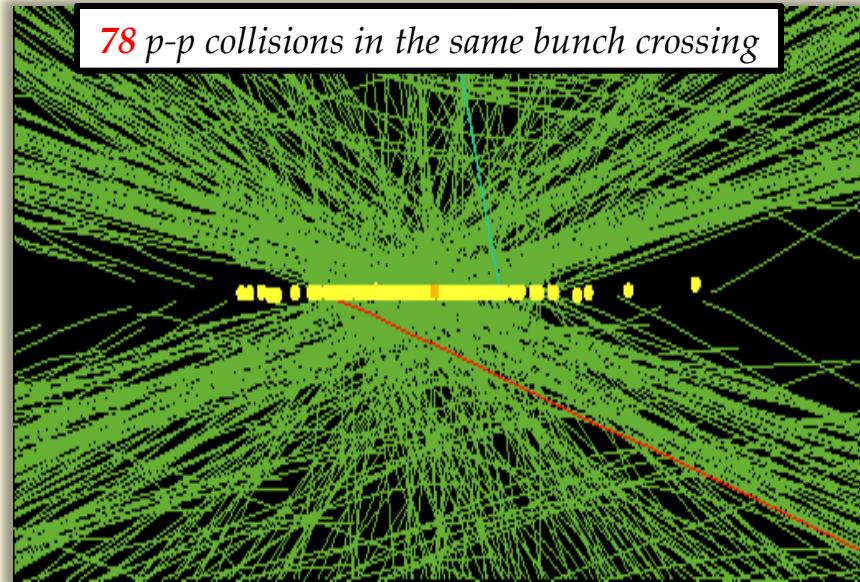
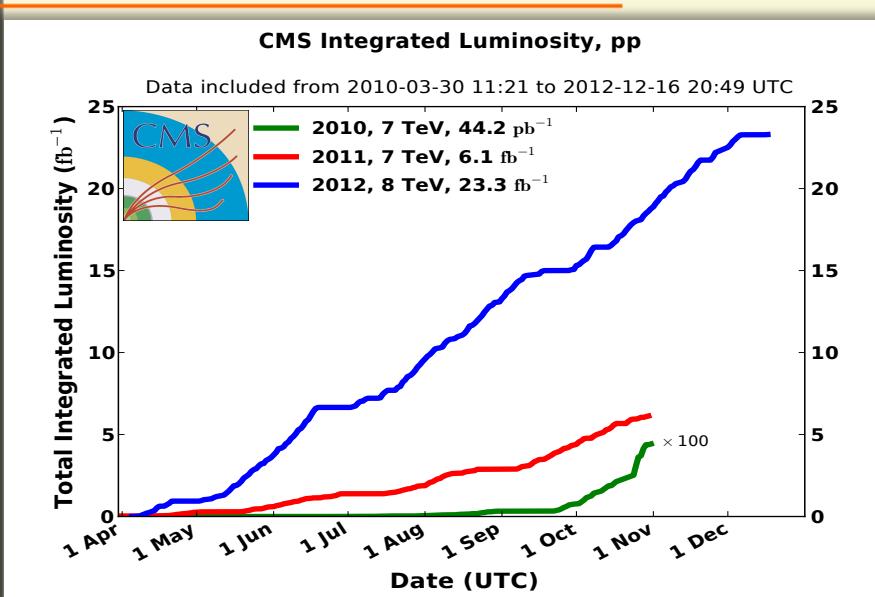


# The CMS and ATLAS detectors



*“General purpose” detectors to cover full physics program with LHC*

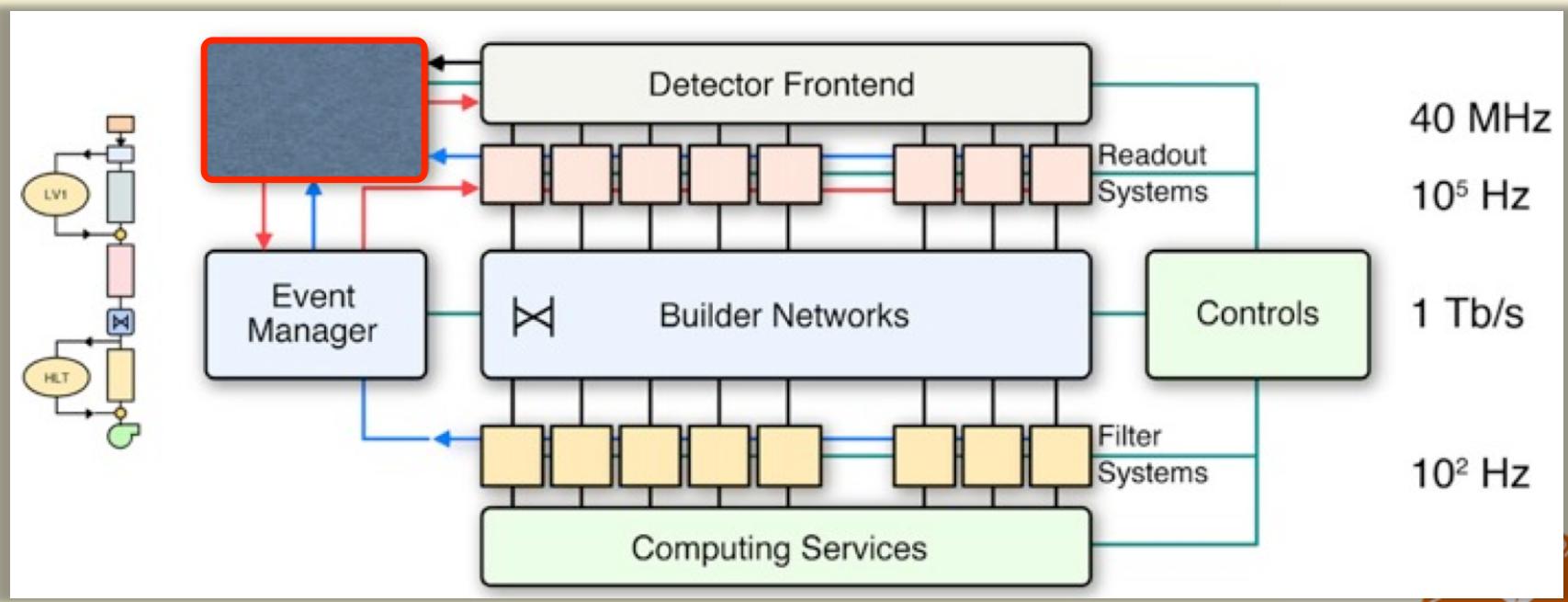
# LHC performance



- Peak luminosity of **7.67 nb<sup>-1</sup>sec<sup>-1</sup>**
- Inelastic proton-proton cross section at 8 TeV: ~70 mb
  - **~540M p-p** interactions per second @ peak luminosity (70x7.67)
  - **20M** times proton bunches cross each other per second (when bunch spacing is 50ns)
  - The average numbers of interaction per crossing (pile-up): **27**
- Approximately **15 PB/year** of data
  - Huge amount of data to process: **400M jobs/month** running on the Grid

# Event selection

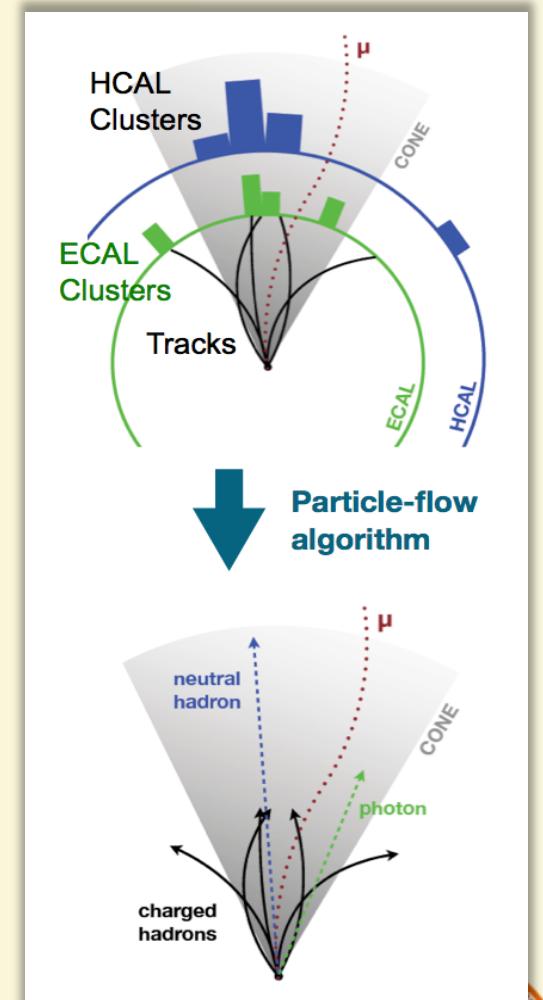
- Bunches of protons ( $\sim 10^{11}$  protons in each bunch) cross each other at CMS/ATLAS at 20~40 MHz
- Trigger system to select only interesting events for further processing
  - Tiered system of triggering (2 levels at CMS, 3 levels at ATLAS)
  - Reduce the output rate down to  $\sim 500$  Hz



CMS Trigger and DAQ

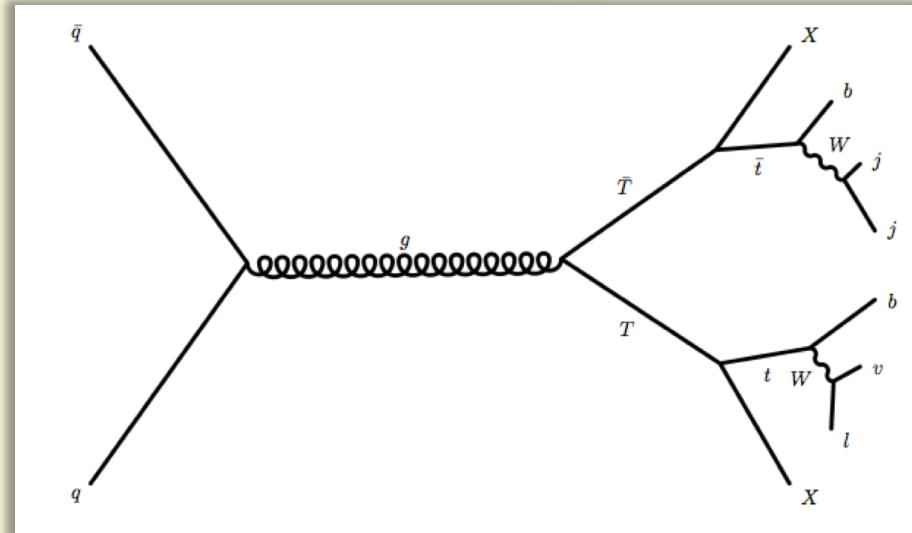
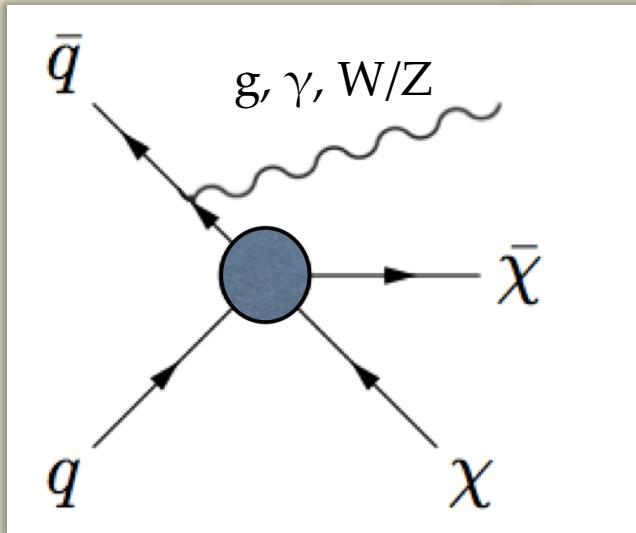
# Event reconstruction

- Visible, particles
  - Charged leptons ( $e, \mu, \tau$ ), photons, neutral and charged hadrons
  - Identified by particle flow algorithm in CMS, detector based reconstruction in ATLAS
- Jets: collimated spray of stable particles
  - Clustered by jet-clustering algorithm ( $\text{anti-}k_T$ )
  - Can be “tagged” to identify origin (b-quark, boosted W)
- Weakly interacting stable particles
  - E.g. neutrinos: inferred from imbalance in the transverse energy
  - Cleaned from detector noise, cosmic muons, etc..



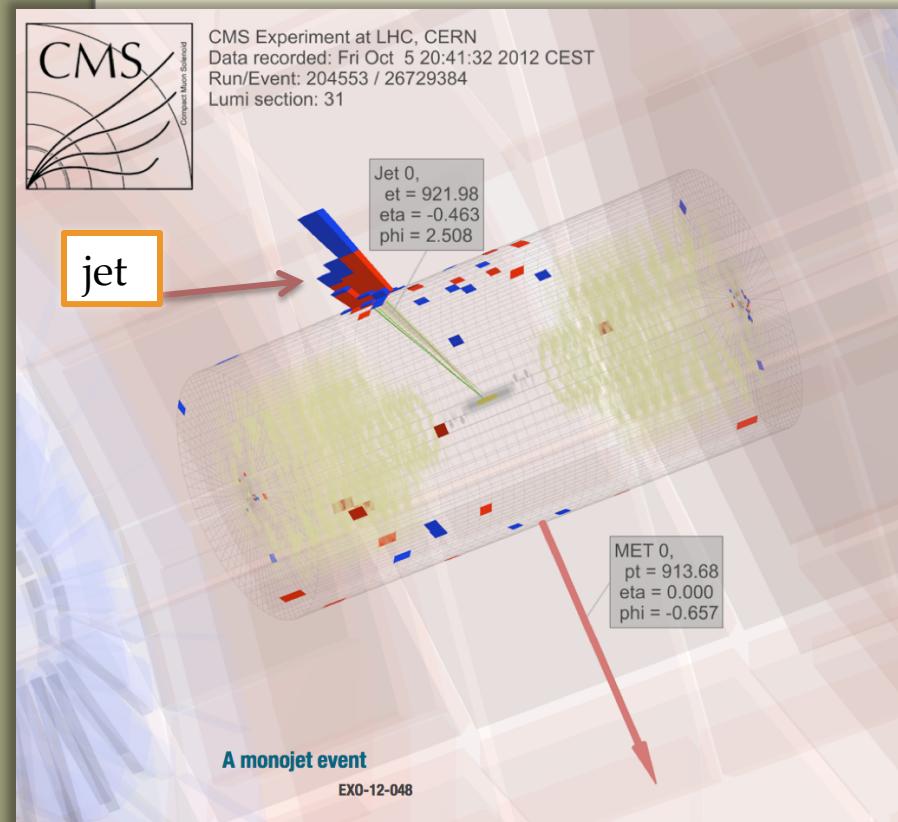
Particle Flow in CMS

# LHC phenomenology

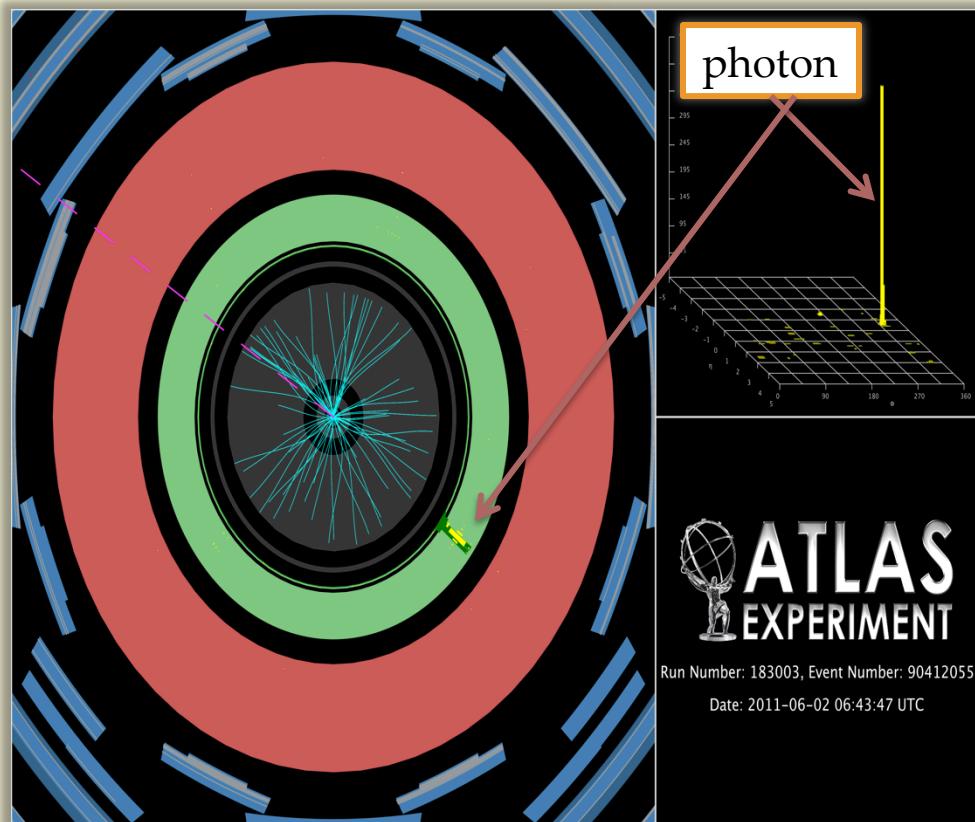


- Assumption: **DM interacts with the SM particles**
- In framework of EFT, assume DM is a Dirac
  - Identify DM candidate events by tagging ISR jet/photon/W or Z
  - Coupling between SM and DM can be evaluated, results can be compared with direct detection results
- Colored production followed by decays to WIMPs
  - Many SUSY searches in CMS and ATLAS (*not covered here*)

# Experimental signatures



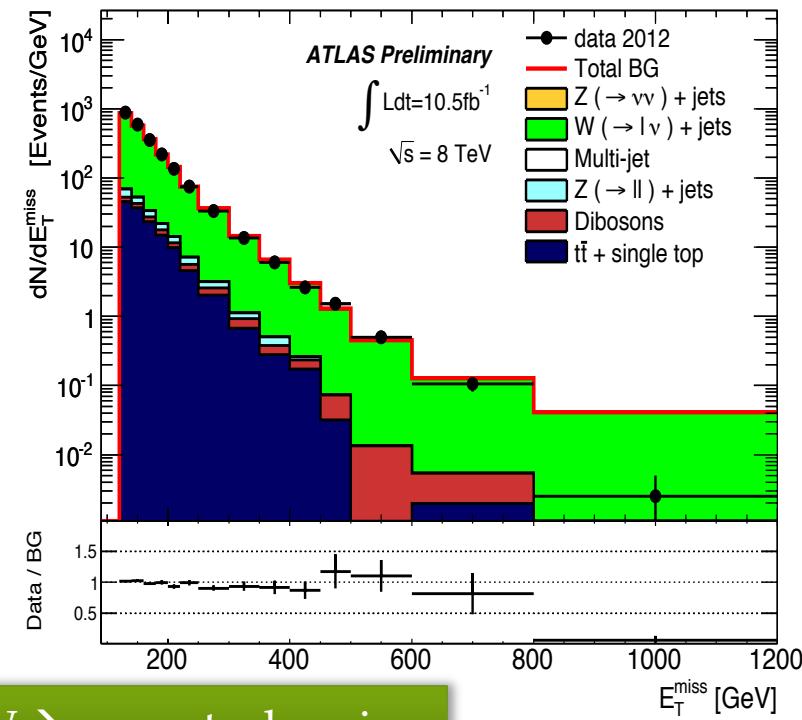
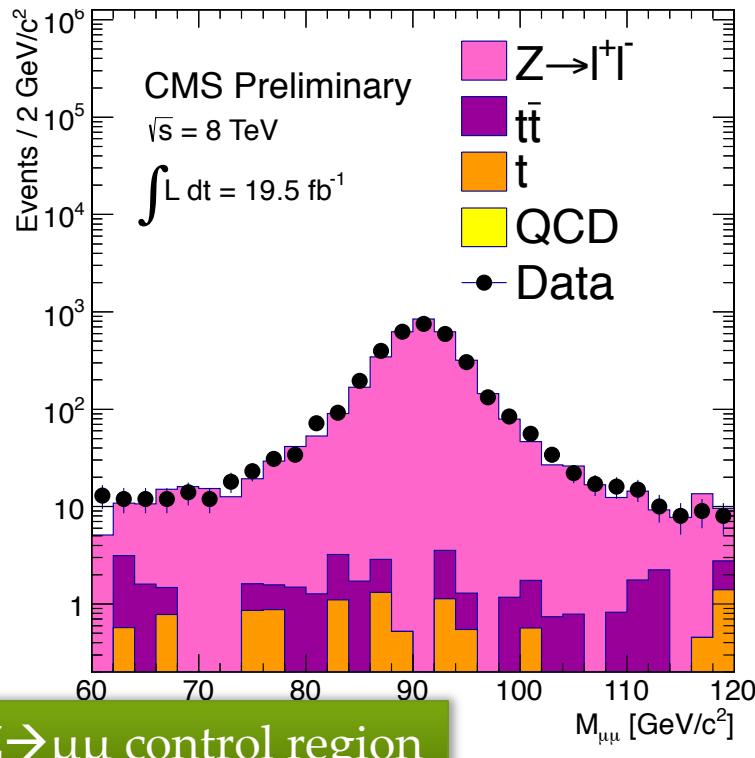
Monojet event in CMS



Monophoton event in ATLAS

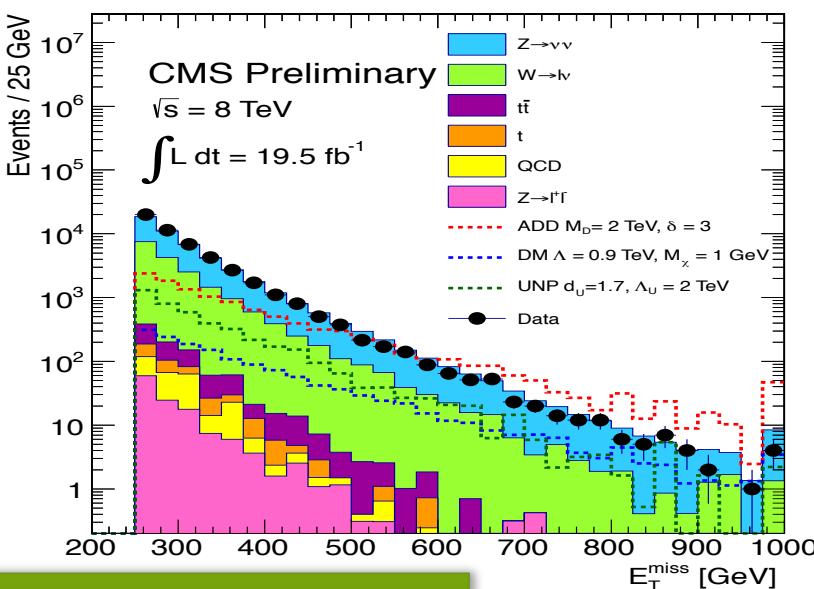
# Monojet searches

- Main backgrounds from  $Z \rightarrow vv$  and  $W \rightarrow lv$  (lepton is lost,  $\tau$  hadronic)
  - $Z \rightarrow vv$  is estimated from  $Z \rightarrow \mu\mu$ : similar kinematic characteristics (CMS) or from data/MC ratio in enriched control sample (ATLAS)
  - $W \rightarrow lv$  from  $W \rightarrow \mu\nu$ , understand the Data/MC scale factors

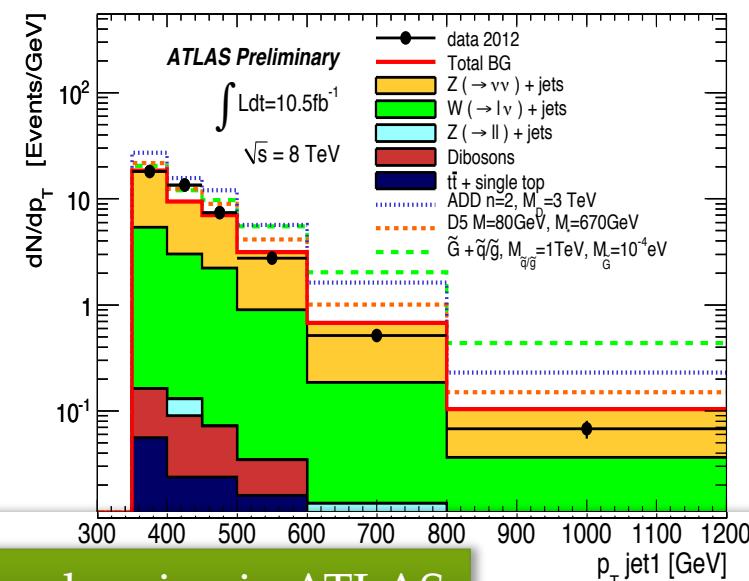


# Monojet results

- Event selections in CMS (ATLAS):
  - $p_T(j_1) > 110$  (120) GeV in  $|\eta| < 2.4$  (2.0); no more than 2 jets with  $p_T > 30$  GeV in  $|\eta| < 4.5$
  - Reject events with signatures of anomalous calorimeter noise
  - no isolated charged leptons with  $p_T > 10 \sim 20$  GeV
- Several signal regions defined:
  - CMS: MET > 250-550 GeV; ATLAS:  $p_T(j1) > 120$ -500, MET>120-500 GeV



Signal region in CMS



Signal region in ATLAS

# Monojet results

$E_T^{\text{miss}}$ (GeV) $\rightarrow$	> 250	> 300	> 350	> 400	> 450	> 500	> 550
Z( $\nu\nu$ )+jets	$30600 \pm 1493$	$12119 \pm 640$	$5286 \pm 323$	$2569 \pm 188$	$1394 \pm 127$	$671 \pm 81$	$370 \pm 58$
W+jets	$17625 \pm 681$	$6042 \pm 236$	$2457 \pm 102$	$1044 \pm 51$	$516 \pm 31$	$269 \pm 20$	$128 \pm 13$
t $\bar{t}$	$470 \pm 235$	$175 \pm 87.5$	$72 \pm 36$	$32 \pm 16$	$13 \pm 6.5$	$6 \pm 3.0$	$3 \pm 1.5$
Z( $\ell\ell$ )+jets	$127 \pm 63.5$	$43 \pm 21.5$	$18 \pm 9.0$	$8 \pm 4.0$	$4 \pm 2.0$	$2 \pm 1.0$	$1 \pm 0.5$
Single t	$156 \pm 78.0$	$52 \pm 26.0$	$20 \pm 10.0$	$7 \pm 3.5$	$2 \pm 1.0$	$1 \pm 0.5$	$0 \pm 0$
QCD Multijets	$177 \pm 88.5$	$76 \pm 38.0$	$23 \pm 11.5$	$3 \pm 1.5$	$2 \pm 1.0$	$1 \pm 0.5$	$0 \pm 0$
Total SM	$49154 \pm 1663$	$18506 \pm 690$	$7875 \pm 341$	$3663 \pm 196$	$1931 \pm 131$	$949 \pm 83$	$501 \pm 59$
Data	50419	19108	8056	3677	1772	894	508
Exp. upper limit	3580	1500	773	424	229	165	125
Obs. upper limit	4695	2035	882	434	157	135	131

CMS

	Background Predictions $\pm$ (stat,data) $\pm$ (stat,MC) $\pm$ (syst.)			
	SR1	SR2	SR3	SR4
Z ( $\rightarrow \nu\nu$ )+jets	$173600 \pm 500 \pm 1300 \pm 5500$	$15600 \pm 200 \pm 300 \pm 500$	$1520 \pm 50 \pm 90 \pm 60$	$270 \pm 30 \pm 40 \pm 20$
W $\rightarrow \tau\nu$ +jets	$87400 \pm 300 \pm 800 \pm 3700$	$5580 \pm 60 \pm 190 \pm 300$	$370 \pm 10 \pm 40 \pm 30$	$39 \pm 4 \pm 11 \pm 2$
W $\rightarrow e\nu$ +jets	$36700 \pm 200 \pm 500 \pm 1500$	$1880 \pm 30 \pm 100 \pm 100$	$112 \pm 5 \pm 18 \pm 9$	$16 \pm 2 \pm 6 \pm 2$
W $\rightarrow \mu\nu$ +jets	$34200 \pm 100 \pm 400 \pm 1600$	$2050 \pm 20 \pm 100 \pm 130$	$158 \pm 5 \pm 21 \pm 14$	$42 \pm 4 \pm 13 \pm 8$
Z $\rightarrow \tau\tau$ +jets	$1263 \pm 7 \pm 44 \pm 92$	$54 \pm 1 \pm 9 \pm 5$	$1.3 \pm 0.1 \pm 1.3 \pm 0.2$	$1.4 \pm 0.2 \pm 1.5 \pm 0.2$
Z/ $\gamma^*$ ( $\rightarrow \mu^+\mu^-$ )+jets	$783 \pm 2 \pm 35 \pm 53$	$26 \pm 0 \pm 6 \pm 1$	$2.7 \pm 0.1 \pm 1.9 \pm 0.3$	–
Z/ $\gamma^*$ ( $\rightarrow e^+e^-$ )+jets	–	–	–	–
Multijet	$6400 \pm 90 \pm 5500$	$200 \pm 20 \pm 200$	–	–
t $t$ + single t	$2660 \pm 60 \pm 530$	$120 \pm 10 \pm 20$	$7 \pm 3 \pm 1$	$1.2 \pm 1.2 \pm 0.2$
Dibosons	$815 \pm 9 \pm 163$	$83 \pm 3 \pm 17$	$14 \pm 1 \pm 3$	$3 \pm 1 \pm 1$
Non-collision background	$640 \pm 40 \pm 60$	$22 \pm 7 \pm 2$	–	–
Total background	$344400 \pm 900 \pm 2200 \pm 12600$	$25600 \pm 240 \pm 500 \pm 900$	$2180 \pm 70 \pm 120 \pm 100$	$380 \pm 30 \pm 60 \pm 30$
Data	350932	25515	2353	268

# Setting limits

- To compare with DM-nucleon limits, assume
  - Interactions are vector, axial-vector, or scalar; DM is Dirac particle

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2} \quad \mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

- Set the mass of mediator to very high mass (tens of TeV)
- Obtain Acceptance x Efficiency using MC samples → obtain limits on  $\sigma_{\chi\chi}$
- Upper limits on cross sections converted to limits on  $\Lambda$  (cutoff scale)

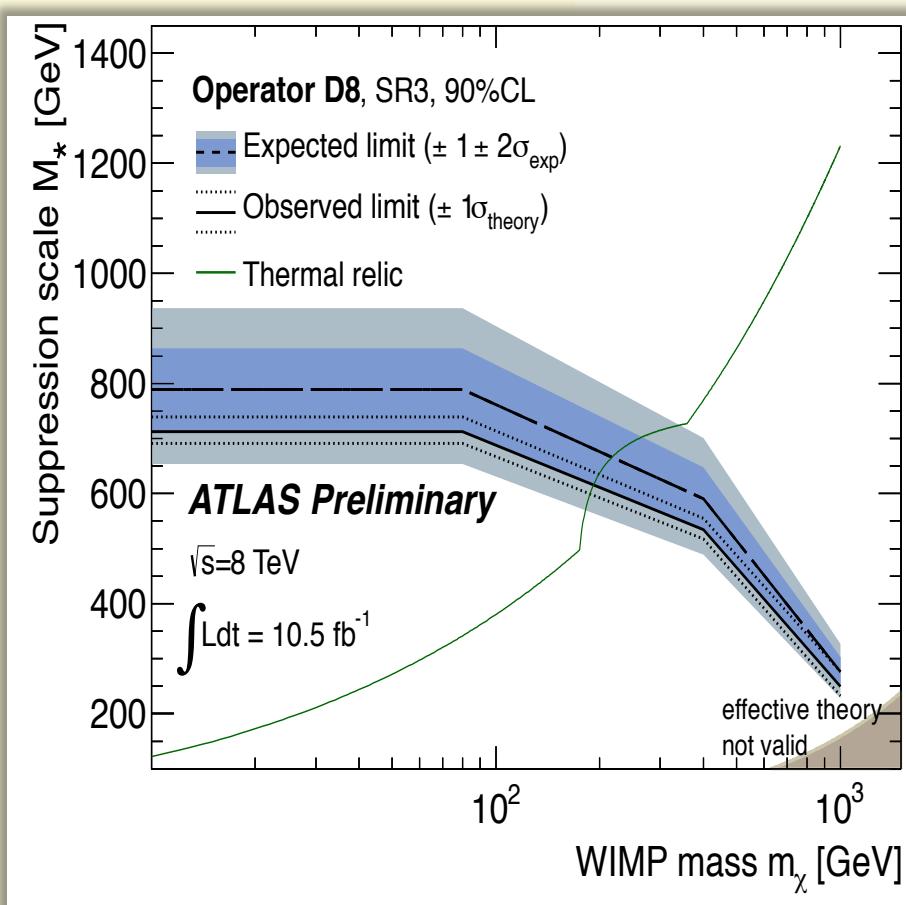
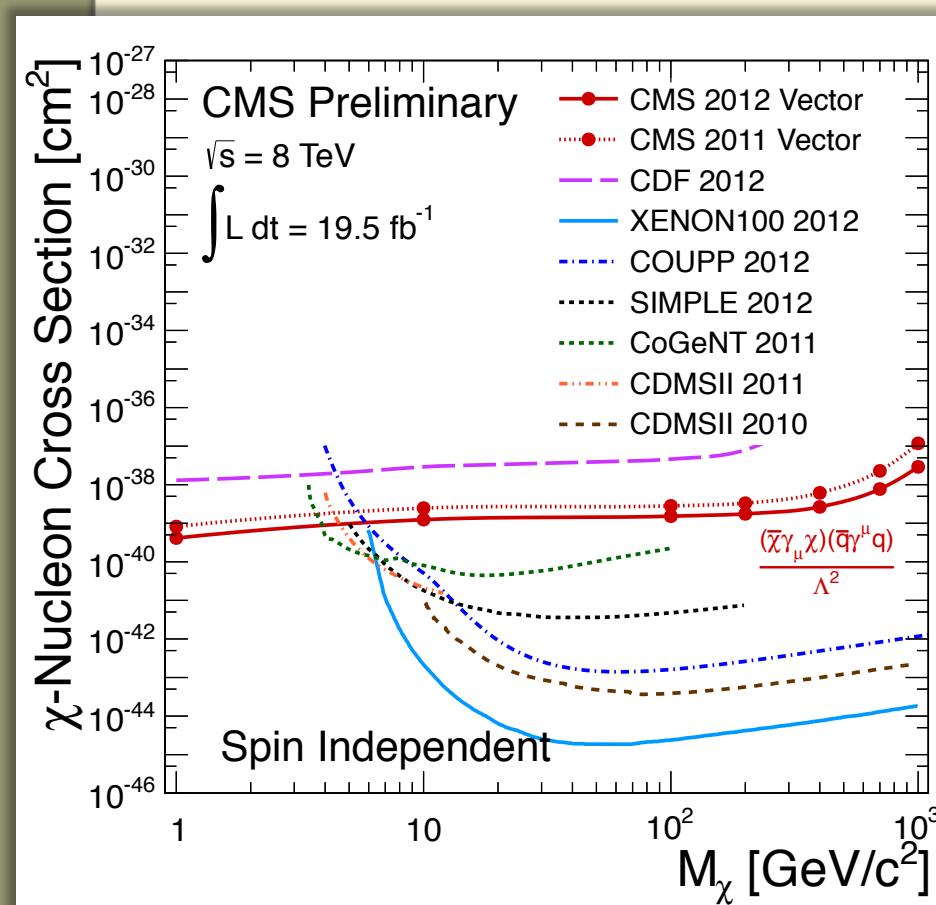
$$\Lambda_{obs}^4 = \frac{\sigma_{calc} \cdot \Lambda_{calc}^4}{\sigma_{obs}}$$

- Translated to limits on DM-nucleon X-section (arXiv:1005.3797)

$$\sigma_{SI} = 9 \frac{\mu^2}{\pi \Lambda^4} \quad \sigma_{SD} = 0.33 \frac{\mu^2}{\pi \Lambda^4} \quad \text{where } \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

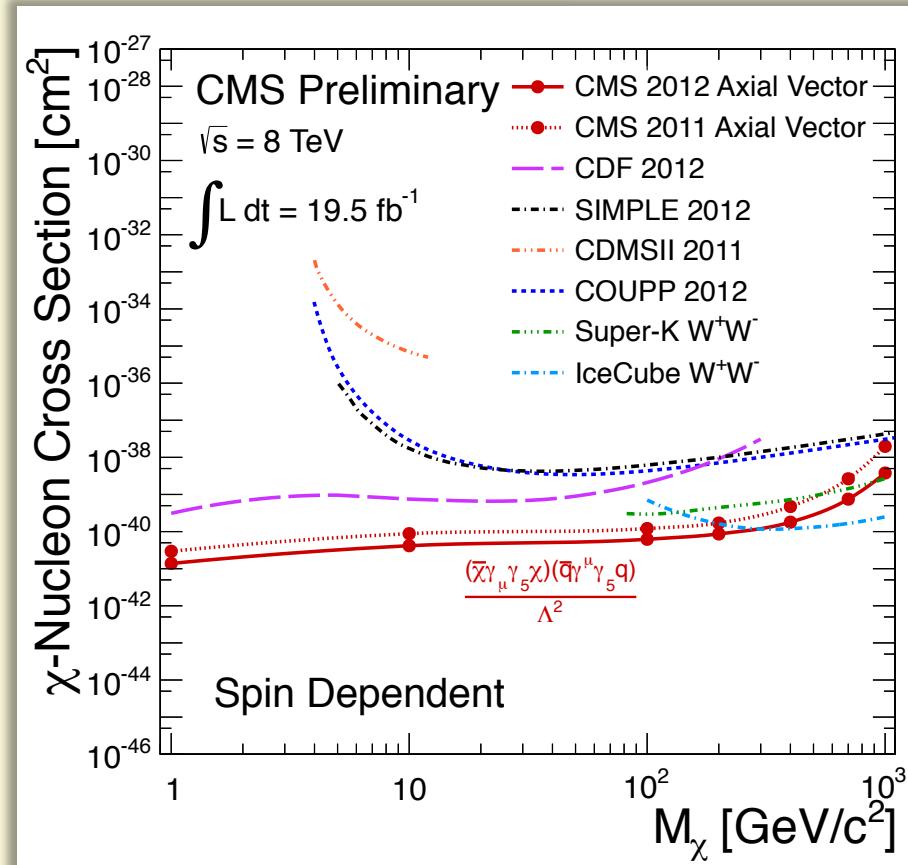
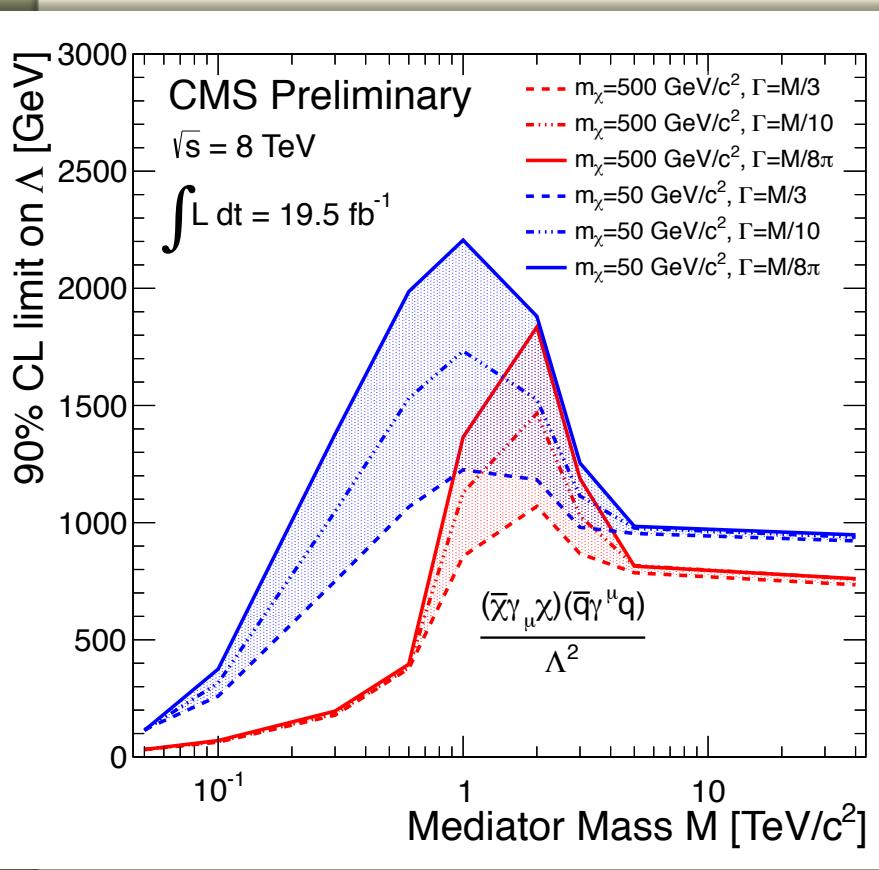


# Monojet limits



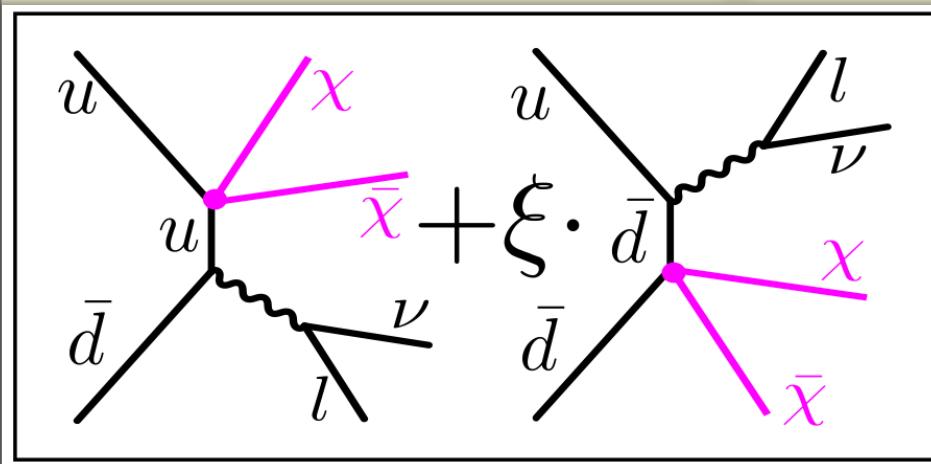
- Best limits below **3.5** GeV for SI DM (hard for the DD experiments)

# Monojet limits

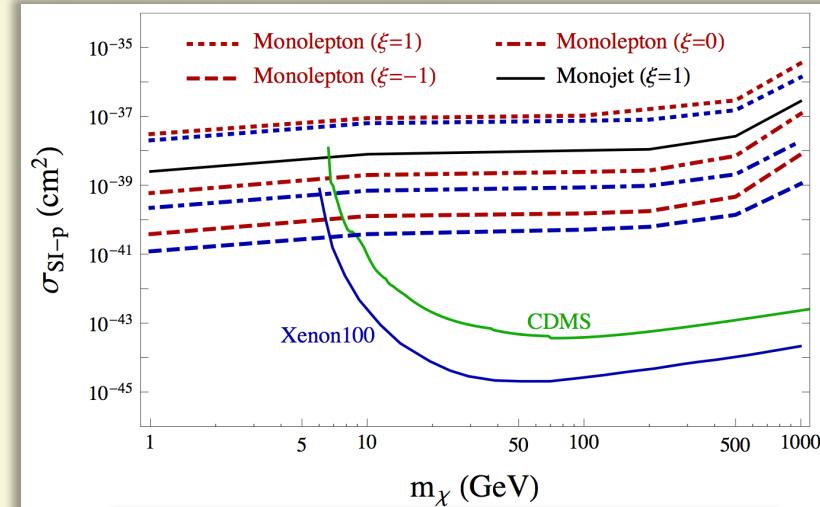


- **Most stringent** constraints over 1-1000 GeV mass for SD DM models

# Mono-lepton searches



Interference between diagrams with  $W$



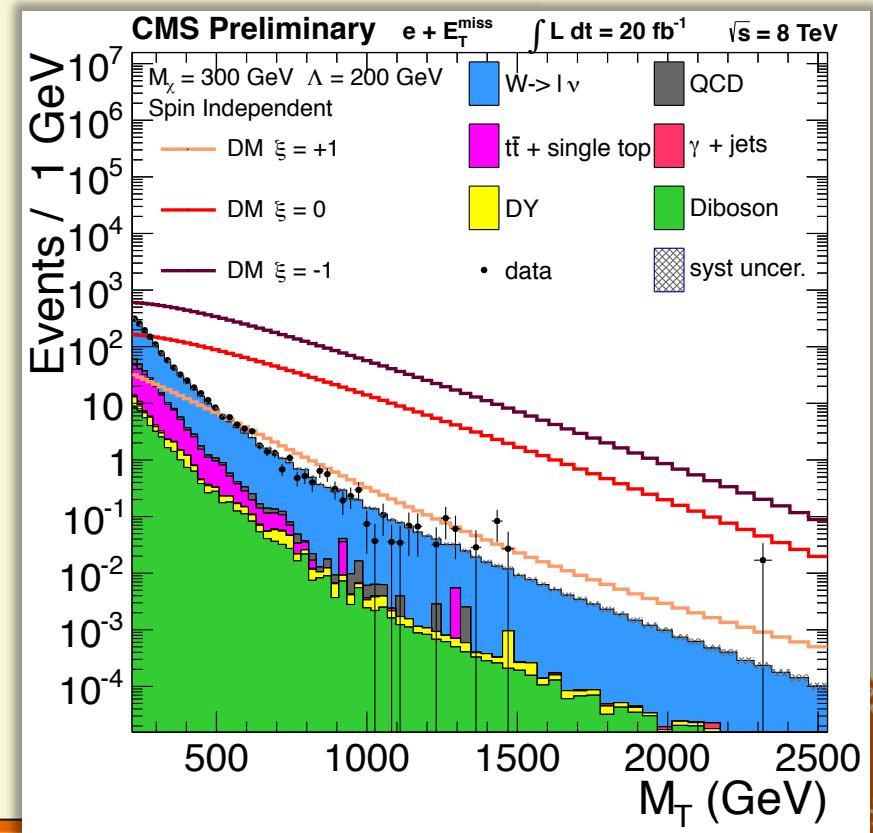
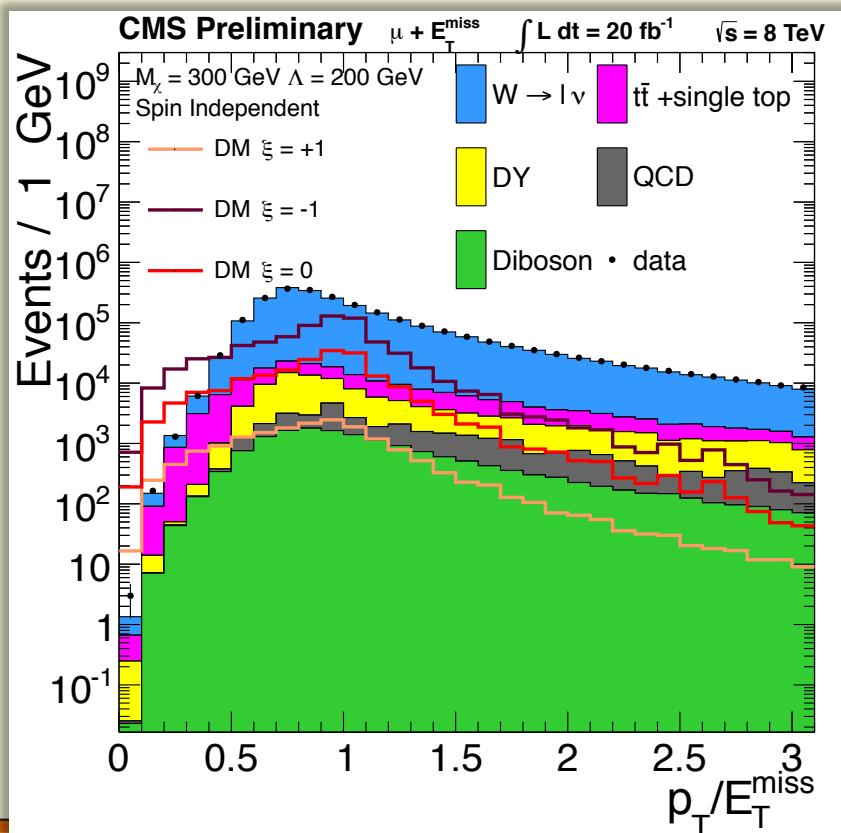
Interpretation of CMS  $W'$  results  
Y.Bai, T.Tait: arXiv:1208.4361

- Monojet and monophoton searches assume equal couplings of the DM particles to up- and down-type quarks
- Higher dimensional operators can alter this relation, yielding other values of  $\xi$  (e.g.  $\xi=-1, 0, -1$ )
  - $\xi=+1$  corresponds to destructive interference,  $\xi=-1$  to constructive
  - Can have higher sensitivity than monojet searches



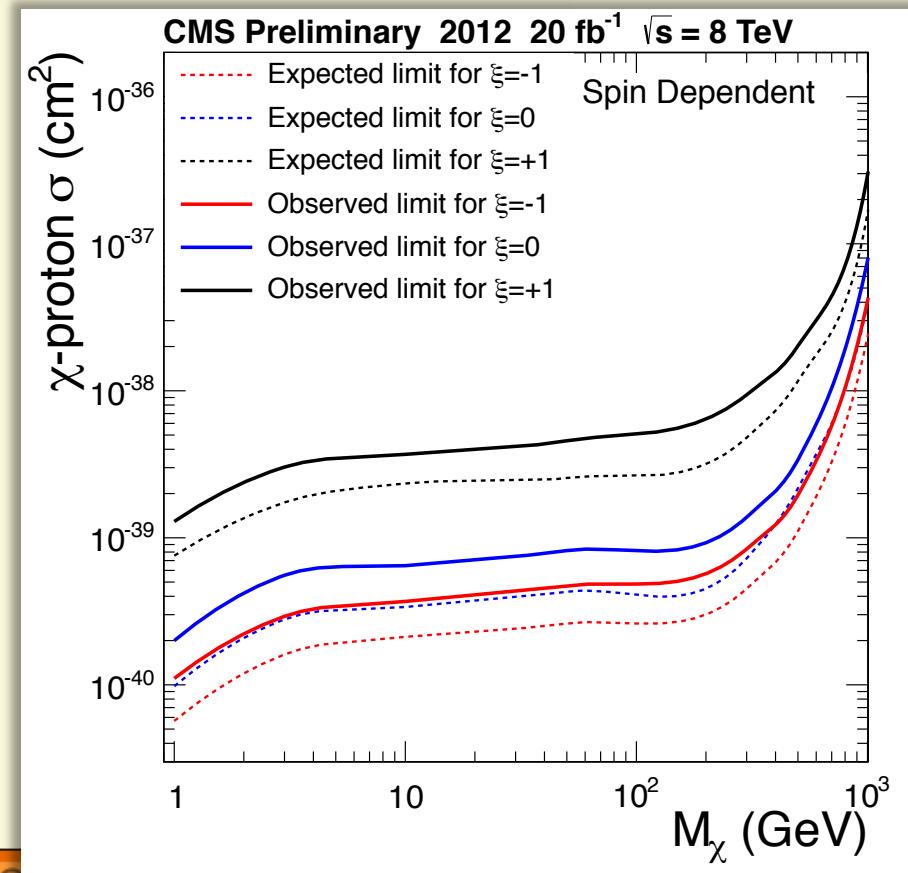
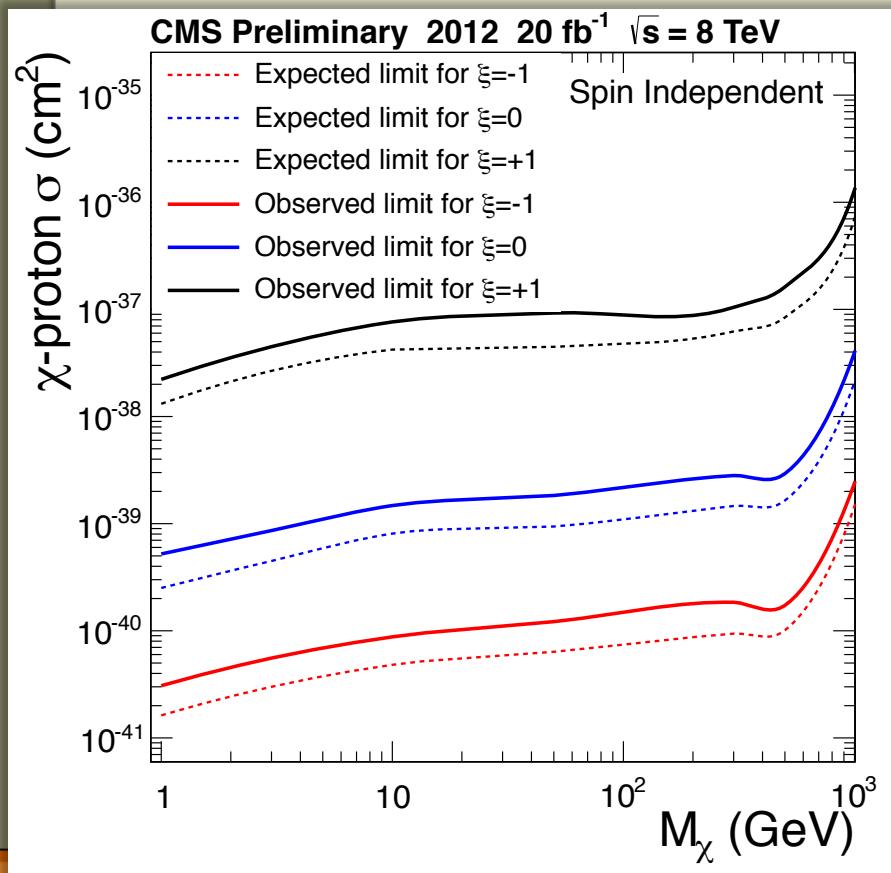
# Mono-lepton search

- Select events with one high  $p_T$  muon ( $\text{ele}) > 45$  (100) GeV
- Back-to-back kinematics  $0.4 < p_T(\ell)/\text{MET} < 1.5$ ;  $\Delta\phi(\ell, \nu) > 0.8\pi$
- Backgrounds determined from simulation, as in  $W'$  search



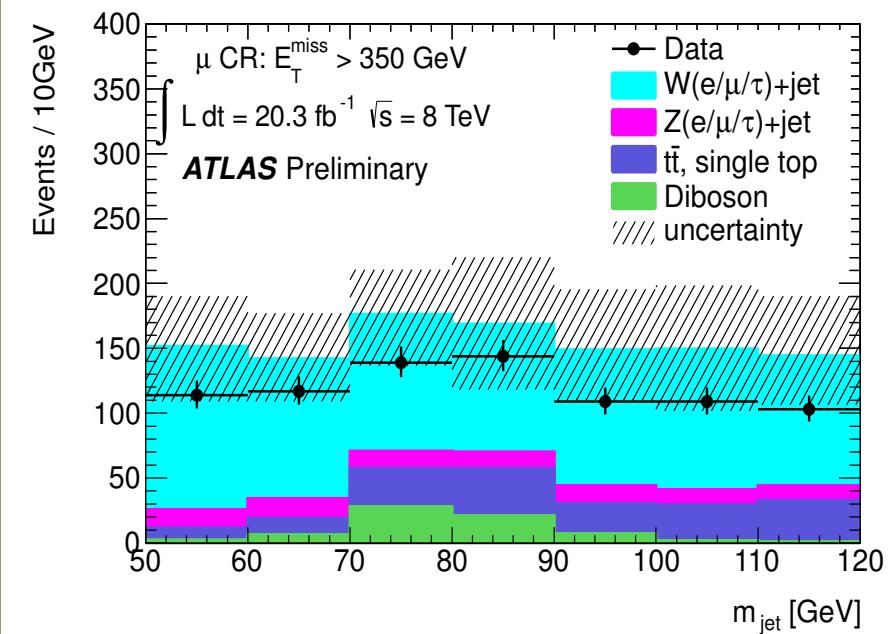
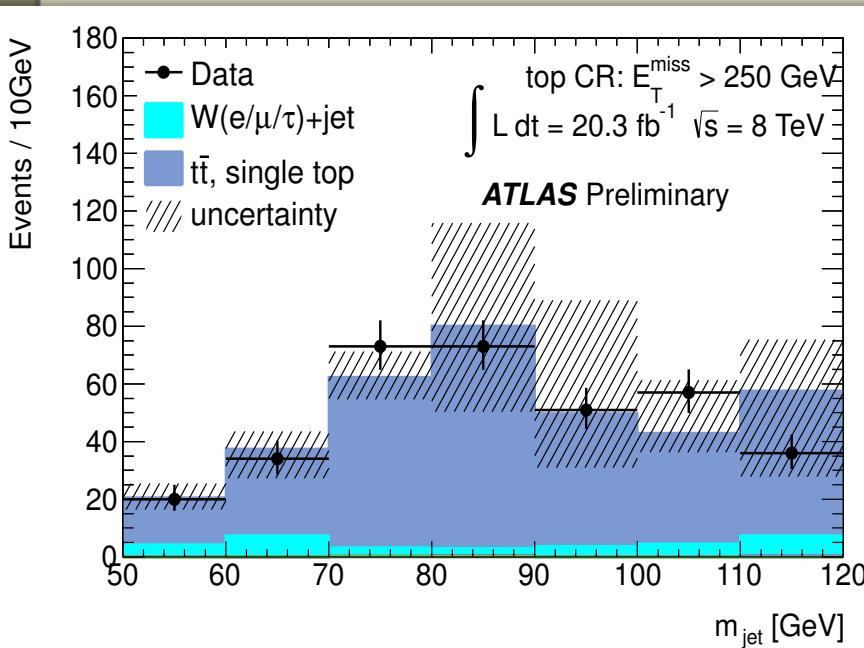
# Mono-lepton searches

- Data consistent with SM expectations, set exclusion limits
- Excluded  $\Lambda < 1000/700/300 \text{ GeV}$  for  $\xi = -1/0/+1$ 
  - for both vector and axial-vector coupling.



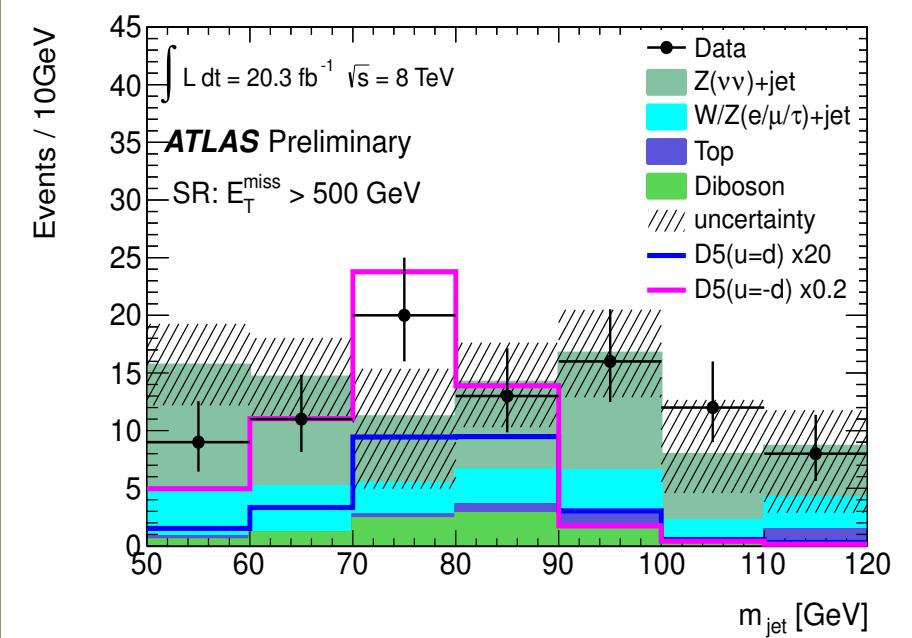
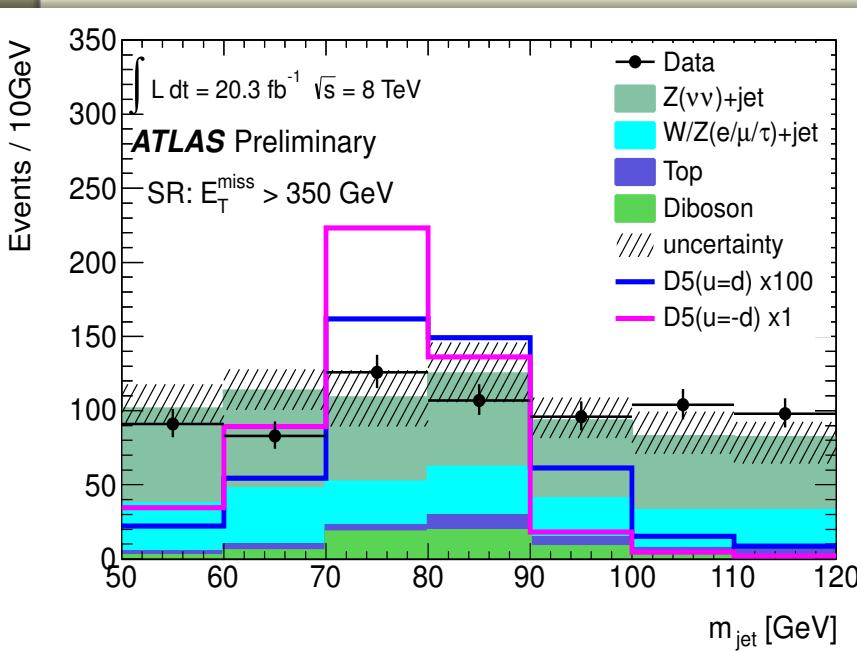
# Mono-W/Z search

- Look for hadronic decays of the W or Z bosons from  $W\chi\chi$  or  $Z\chi\chi$ 
  - Reconstructed W or Z as a single massive jet (CA jet) plus MET
- Validated in control regions
  - top dominated: one muon, one CA jet ( $p_T > 250 \text{ GeV}$ ,  $|\eta| < 1.2$ ), two anti- $k_T$  jets ( $p_T > 40 \text{ GeV}$ ,  $|\eta| < 4.5$ ), at least one b-tag and  $\text{MET} > 250 \text{ GeV}$
  - W dominated: one muon and  $\text{MET} > 350 \text{ GeV}$



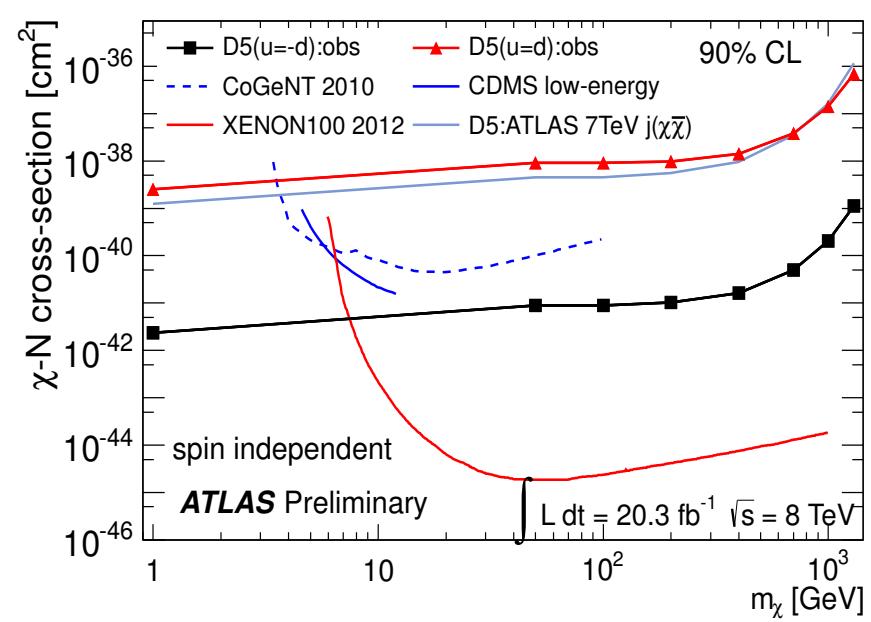
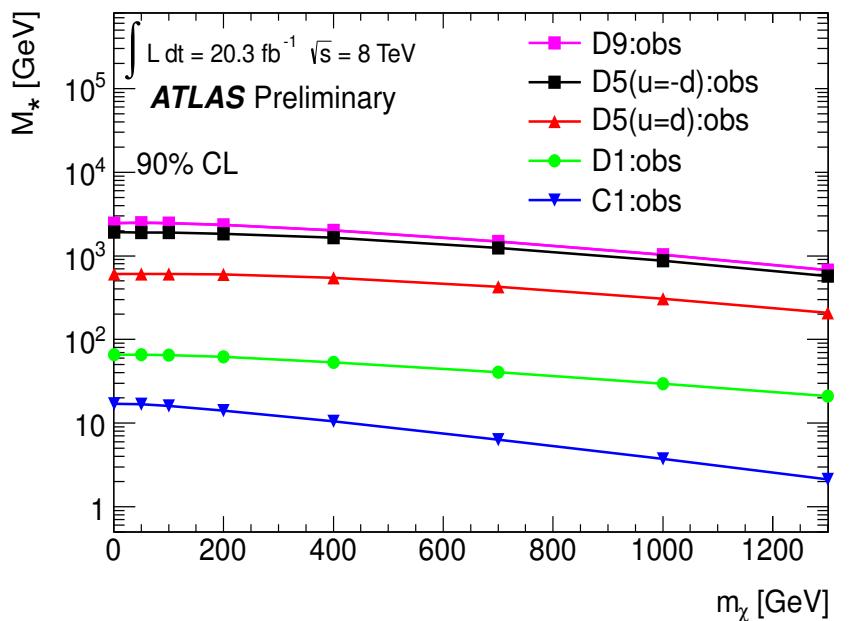
# Mono-W/Z search

- Signal region selections:
  - CA jet with  $p_T > 250 \text{ GeV}$ ,  $|\eta| < 1.2$ ;  $50 < m_{\text{jet}} < 120 \text{ GeV}$ ;  $\min(p_{T1}, p_{T2})\Delta R / m_{\text{jet}} > 0.4$ , no muon, electron or photon; two SR with  $\text{MET} > 350$  and  $500 \text{ GeV}$
- Dominant backgrounds from  $Z \rightarrow vv$ , and  $W+\text{jets}$  or  $Z \rightarrow \ell\ell + \text{jets}$  where leptons are missed
  - Estimate from data with inverted muon veto

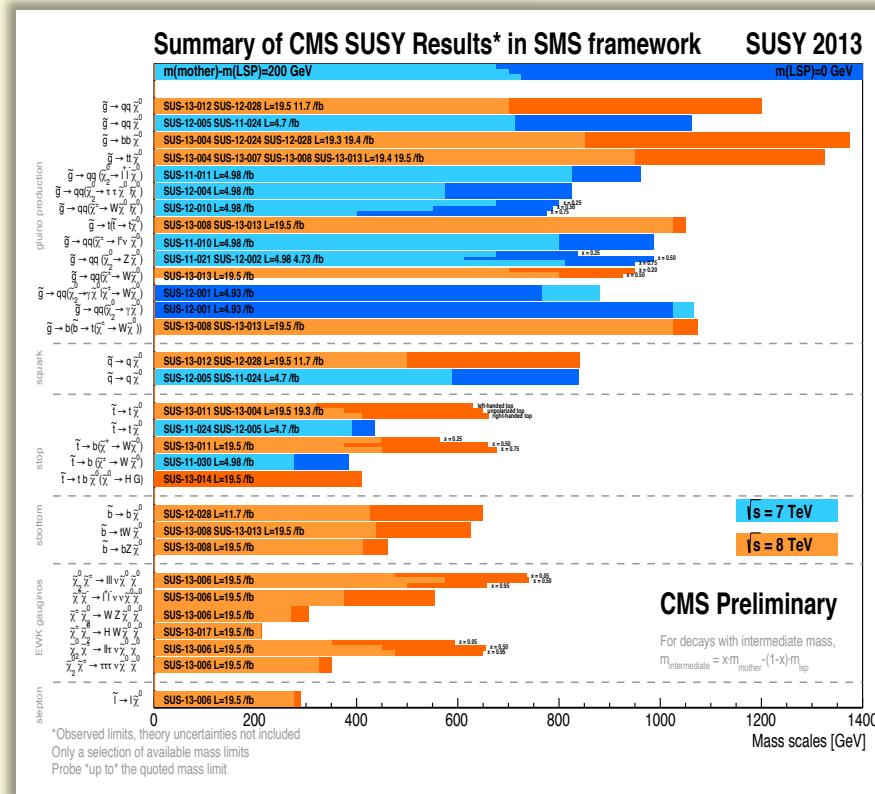
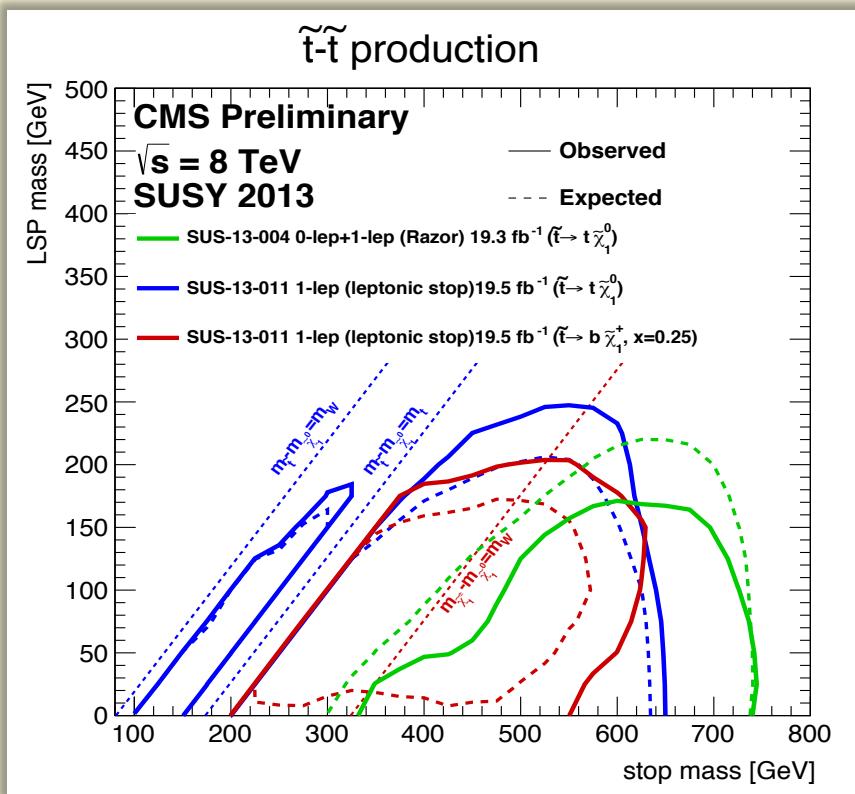


# Mono-W/Z limits

Process	$E_T^{\text{miss}} > 350 \text{ GeV}$	$E_T^{\text{miss}} > 500 \text{ GeV}$
$Z \rightarrow \nu\bar{\nu}$	$400^{+39}_{-34}$	$54^{+8}_{-10}$
$W \rightarrow \ell^\pm \nu, Z \rightarrow \ell^\pm \ell^\mp$	$210^{+20}_{-18}$	$22^{+4}_{-5}$
$WW, WZ, ZZ$	$57^{+11}_{-8}$	$9.1^{+1.3}_{-1.1}$
$t\bar{t}, \text{ single } t$	$39^{+10}_{-4}$	$3.7^{+1.7}_{-1.3}$
Total	$710^{+48}_{-38}$	$89^{+9}_{-12}$
Data	705	89



# Other searches



- Rich program of searches in SUSY at CMS and ATLAS
  - Various interpretations, most recently focusing on SMS
- New search strategies
  - Razor based search for DM in hadronic final state coming soon



# Conclusion

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- LHC experiments provide broadly sensitive searches
- Predictions for SM backgrounds consistent with data
  - Set limits on DM production cross-section
- Results interpreted in EFT framework
  - Interpret in terms of  $\chi$ -nucleon cross-section limits
  - Provide competitive and complimentary results to DM searches, in some cases world best limits
- Substantial improvement expected from LHC Run2 @ 14 TeV



# Backup

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# DM operators

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	$m_q/M_*^3$
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/M_*^3$
D3	$\bar{\chi}\chi\bar{q}\gamma^5q$	$im_q/M_*^3$
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	$m_q/M_*^3$
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	$i/M_*^2$
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	$m_q/M_*^2$
C2	$\chi^\dagger\chi\bar{q}\gamma^5q$	$im_q/M_*^2$
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.



# ATLAS/CMS performance overview

	ATLAS (7 ktons)	CMS (12.5 ktons)
INNER TRACKER	<ul style="list-style-type: none"> <li>Silicon pixels + strips</li> <li>TRT with particle identification</li> <li><math>B = 2 \text{ T}</math></li> <li><math>\sigma(p_T) \sim 3.8\% \text{ (at } 100 \text{ GeV, } \eta = 0\text{)}</math></li> </ul>	<ul style="list-style-type: none"> <li>Silicon pixels + strips</li> <li>No dedicated particle identification</li> <li><math>B = 3.8 \text{ T}</math></li> <li><math>\sigma(p_T) \sim 1.5\% \text{ (at } 100 \text{ GeV, } \eta = 0\text{)}</math></li> </ul>
MAGNETS	<ul style="list-style-type: none"> <li>4 Magnets</li> <li>Solenoid + Air-core muon toroids</li> <li>Calorimeters outside solenoid field</li> </ul>	<ul style="list-style-type: none"> <li>1 Magnet</li> <li>Solenoid</li> <li>Calorimeters inside field</li> </ul>
EM CALORIMETER	<ul style="list-style-type: none"> <li>Pb / Liquid Ar sampling accordion</li> <li><math>\sigma(E) \sim 10\text{--}12\%/\sqrt{E} \oplus 0.2\text{--}0.35\%</math></li> <li>Longitudinal segmentation</li> <li>Saturation at <math>\sim 3 \text{ TeV}</math></li> </ul>	<ul style="list-style-type: none"> <li>PbWO<sub>4</sub> scintillation crystals</li> <li><math>\sigma(E) \sim 3\text{--}5.5\%/\sqrt{E} \oplus 0.5\%</math></li> <li>No longitudinal segmentation</li> <li>Saturation at <math>1.7 \text{ TeV}</math></li> </ul>
HAD CALORIMETER	<ul style="list-style-type: none"> <li>Fe / Scint. tiles (EC: Cu-liquid Ar)</li> <li><math>\sigma(E) \sim 45\%/\sqrt{E} \oplus 1.3\% \text{ (Barrel)}</math></li> </ul>	<ul style="list-style-type: none"> <li>Cu (EC: brass) / Scint. tiles</li> <li>Tail catchers outside solenoid</li> <li><math>\sigma(E) \sim 100\%/\sqrt{E} \oplus 8\% \text{ (Barrel)}</math></li> </ul>
MUON	<ul style="list-style-type: none"> <li>Drift tubes &amp; CSC (fwd) + RPC/TGC</li> <li><math>\sigma(p_T) \sim 10.5\% / 10.4\% \text{ (1 TeV, } \eta = 0\text{)}</math> (standalone / combined with tracker)</li> </ul>	<ul style="list-style-type: none"> <li>Drift tubes &amp; CSC (EC) + RPC</li> <li><math>\sigma(p_T) \sim 13\% / 4.5\% \text{ (1 TeV, } \eta = 0\text{)}</math> (standalone / combined with tracker)</li> </ul>

